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HOW THE BRAIN WORKS

RAYMOND SCANLON
MARK JOHNSON

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US ARMY ARMAMENT RESEARCH,
DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
WATERVLIET, N.Y. 12189-4050

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What is a thought except a movement that is not connected to a motor neuron.

Walle Nauta

INTRODUCTION

We explain how the brain works; how a simple structure, following a small set of rules, produces the action called thinking by disconnecting the movement from the pre-motor and motor areas of the neocortex. Any description of the working brain must be trivial since there is no mental component. Those who would complain of shallowness should consider the implications of materialism.

This is how we see the vertebrate brain. Signal energy flows in from the left through the box labeled sensors. It fans-out through the brain (Figure 1) and then fans-in and becomes a motor program (movement). The program flows through to the motors (muscles). The brain is a homeostat: it keeps the body in the happy center of life. If the organism has eaten and is warm and secure, the brain is idle; if it is a mammal, it may dream.

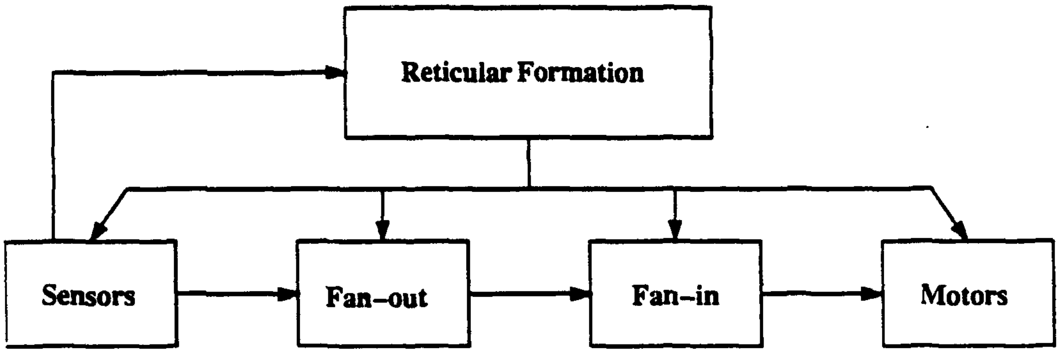

Figure 1. A simplified vertebrate brain.

Sitting on top is the reticular formation; it serves to alert the brain to the presence of the predator. The reticular formation is a fundamental element in the vertebrate brain. It is present in the most primitive jawless fishes; it is present in man. It works by habituating to the environment; any change signals the presence of the predator. It wakes up the brain and prepares it for evasive action by lowering the effective threshold of the individual neurons. A homeostat with a predator alarm describes the pre-mammalian brain.

The mammals add a new dimension to the brain--the relay nuclei of the thalamus and the thalamic reticular nucleus that controls them (Figure 2). Signal energy flows in from the left through the box labeled sensors. Energy passes through the lateral geniculate body (vision), medial geniculate body (hearing), and the ventrobasal nucleus of the thalamus (body senses) on its way to the cortex.

After the signal energy passes through, it fans-out in the cortex, branching continuously. When the fan-out is complete, the signal energy begins to fan-in until it settles on a motor program that starts the motors (muscles).

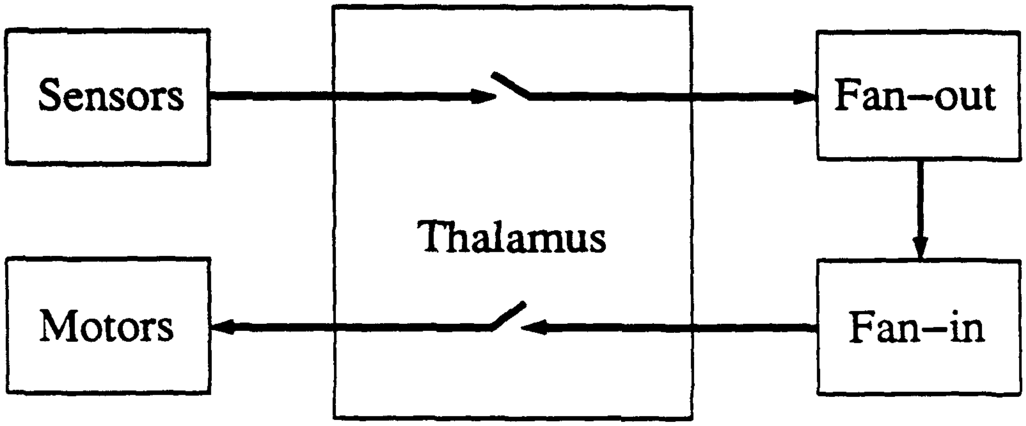

Figure 2. A simplified mammalian brain.

Some neurons in the boxes labeled fan-out and fan-in connect to neurons in the reticular nucleus of the thalamus. These neurons in the reticular nucleus can stop the flow of signal energy coming in or the motor program going out or both. If the activated motor program or the present constellation of signal energy has led to bad results in the past, the bad feeling strengthened the synapses between these active neurons and the neurons in the reticular nucleus. Now the new signal energy turns them up anew, and in turn they activate the neurons in the reticular nucleus that inhibit the relay of the motor program. The mammal hesitates. The signal energy continues to circulate (with feedback) in the fan-out fan-in section of the brain. This may lead to the activation of another motor program that does not turn on the reticular nucleus. It will flow through to the motors. We call this thinking and reaching a decision.

The environment fine-tunes the brain. The genome that mutated and produced this system survived. There is not enough genome to specify a brain completely, synapse by synapse, but there is enough to provide a plastic structure that can get by in life. Rules laid down genetically govern the plasticity, rules that allow the environment to make the final adjustments to the brain.

The schematic of the brain exists in the genes; they produce a working circuit. There is insufficient genome to specify the location of every synapse. That is not how the genes build the brain; they build it according to rules. Usually they preserve topology; the axons of neighboring neurons end among neighbors. Wide or narrow terminal arborization of axons determines the width of consensus. The precision of the wiring of input to output controls the specificity of response. The associative connections are extremely complex but precisely organized (ref 1).

The brain tells us a story of survival. The neurons have ordered themselves precisely; they sit "like eggs in a crate" genetically positioned to represent the entire history of the living cell. When we are two years old our genes have given us a functioning body directed by a functioning brain. Our brain is ready to have its plasticity fine-tuned by the environment, ready to learn the location of food sources and secure resting places. If food is at hand and life is secure, the brain is idle; it can take up philosophy and mathematical demonstrations.

HOMEOSTASIS

All animal behavior is the result of a homeostat reacting to the world (ref 2). Homeostasis is the tendency of a device to maintain a relative equilibrium, to seek a center in the presence of events that disturb it. This is the way the brain works; it maintains the metabolic balance of the organism. It would keep the body in a pleasant state: not too hot, not too cold, well fed, and secure, always close to the center of the parameters of life. We live in a violent world; we must avoid being eaten while we look for food, water, and a mate. Enough individuals must escape the predator long enough to reproduce. The species that exist on the face of the earth define "enough."

A homeostat in the mammalian body keeps the body temperature within narrow limits. Part of the hypothalamus monitors the temperature of the body. If the temperature rises, the thermostat orders vasodilation and sweating to lower it. If it falls, the thermostat orders peripheral vasoconstriction, piloerection, increased metabolism, and shivering to raise it. Of course a homeostat is only an abstraction; we create an entity and name it; we give it existence. It is an ephemeral thing, a shadow on the wall. A neuron seems more solid; let us talk of neurons. There are warm-sensitive receptors in the preopticanterior hypothalamic area, watching the temperature of the arterial blood passing by. These receptors respond to a rise in temperature with a graded potential. This graded potential controls the rate of firing of interneurons whose axons reach the caudal hypothalamus where they inhibit neurons that are efferent on smooth muscle fibers surrounding elements of the peripheral circulatory system. The peripheral blood system, released from these constricting muscles, dilates under the pressure of the blood and more internal heat reaches the skin.

There are cold-sensing receptors in the skin. They similarly excite interneurons that reach the caudal hypothalamus, but they excite the neurons that trigger the smooth muscles that constrict the peripheral blood system. Now less internal heat reaches the skin. They also excite neurons that terminate on muscles that raise the body hairs and other neurons that trigger a circuit of neurons that produce shivering. They excite neurons that release chemical packets into the blood stream that cause the cells of the body to increase their individual metabolism. Together these events raise the internal temperature of the body.

We can follow this action from neuron to neuron, finding nothing but individual neurons responding to the neurons afferent on them. Each interneuron synapses on many hypothalamic neurons so that they (in effect) take a consensus, but the neurons respond individually. We think of a homeostat as controlling a variable along one dimension--that heat and cold are opposites--but this is an illusion. There are only individual sensors and individual responses. The brain is a homeostat of many homeostats whose actions we choose to see as electrical events. The brain-homeostat can be divided into smaller homeostats: one for hunger-satiety, one for thirsty-not thirsty, one for warm-cold. But there is only one brain, we make the divisions. The brain balances general parameters such as: pain-pleasure, tension-relaxation, and good-bad. As our home thermostat calls for heat, so does the homeostat call for action. The homeostat sends nerve impulses to turn on neurons that will activate muscles. The muscles will push at the environment until the homeostat moves toward neutral. The circuitry cannot be perfect, and eventually the predator eats the organism; we do the best we can. If our stomach musculature contracts on emptiness or our blood sugar lowers, the hypothalamus moves us toward food

smells. If the osmoreceptors in the hypothalamus detect thickened blood, we move toward water. The nervous system interfaces with the world. Signal energy flows in, circulates, and flows out as motor energy. The system reacts swiftly through its electronic capabilities or slowly through the endocrine system.

Avoidance and Approach

A pain system (the periaqueductal gray and the thalamic ventral posterolateral nucleus), a pleasure system (the medial forebrain bundle and the nucleus accumbens septi), and a tension system (the cingulate gyrus) are essential parts of the brain as established by the genes. Pleasure stands for good; pain and tension stand for bad.

If a homeostat is calling for action, we experience a reduction of this call as pleasure. A demand for action by a homeostat, coupled with a blockade of motor programs at the ventral anterior-ventral lateral complex of the thalamus, we call tension. Lowering tension is pleasure. The pleasure/displeasure ratio attached to every experience is the index that ultimately determines all behavior (ref 3).

Sometimes an internal drive causes conflict with the exterior world; pain is the result. "The thalamus is apparently of great significance for the appreciation of pain and temperature, but how it is involved is not known." (ref 1) What we do not know is the mechanism of transfer from objective to subjective pain; we do not know it because we cannot know it. Understanding of the interface between brain and mind is forever withheld from us. A homeostat has a negative and a positive pole. The negative leads to avoidance and the positive to approach. The genome hardwires us to decrease the negative and increase the positive.

All of the homeostatic drives--hunger, thirst, temperature control, and sex--differ from one another in their anatomical and physiological representations and in the behavior attached to them. Yet they all need a built-in criterion of fulfillment. There are only a few of these mechanisms. They can be regarded as the most basic of all drives: to seek pleasure and to avoid displeasure (ref 3).

The homeostats that monitor the interior world interest us, but the homeostat that follows the exterior world fascinates us. It produces the four aspects of behavior: fighting, fleeing, feeding, and sexual activity. When we ask, "How does the brain work?" we are speaking mainly of this one homeostat. There are four systems that drive it: arousal-sleep, pain, tension, and pleasure.

The organism follows its nose and eats anything that tastes good; the wiring is simple. Each olfactory organ sends signal energy straight back into the brain where a good smell becomes a motor program that swings the head toward the smell. The genome defines good and bad; we label "good" those smells it wires the organism to swing toward and "bad" those it wires to avoid.

Inquisitiveness

When awake the organism moves about driven by the hunger, thirst, and sex homeostats. The genes have hardwired an assortment of neurons (throughout the brain but centered in the hypothalamus) to respond to the presence of the opposite sex by initiating sexual activity. Even when the mammal has satisfied hunger, thirst, and sex, an apparently aimless exploratory behavior can appear. We call this curiosity; it stems from novelty. The firing of neurons that did not fire too often in the past we experience as pleasure. This curiosity is an important part of mammalian behavior. Even absent novelty, motor output itself (in mammals) arouses the pleasure center. This is important in games and play.

The Predator Alert

As the neural net evolved, it showed new abilities. The first of these was the detection of the predator. A darkness sensitive placode, dorsally located, served this purpose. We say darkness sensitive because the retina is sensitive to dark, not light. The rods and cones are most active in the dark; light hyperpolarizes them. This dorsal placode, then, would respond to an overhead shadow with a burst of neural activity. This burst of signal energy would energize an evasive maneuver through the internet. The internet involved has become the reticular formation. When the neural plate rolled up to form the neural tube, the placode moved inside. It faced inside and when it moved out to become the retina, it still faced inside. To this day, an overhead shadow startles us.

Habituation characterizes the neurons of the reticular formation. A synapse habituates when it no longer responds to a continued steady input. The reticular formation "habituates" to the environment as its synapses habituate to the ambient signal energy. Any sudden change in the milieu signals the approach of a predator. In the simple world of the filter feeder, anything new signals sudden death. If by some odd chance it is not a predator, a little evasion does no harm (ref 4).

Let the signals change their levels and the reticular formation will turn on and alert the brain. The neurons of the reticular formation send out axonal pulses that lower the threshold of neurons throughout the brain except one area--the reticular nucleus of the thalamus--this area the pulses inhibit. The formation is non-specific; it does not react to any particular signal energy. What the formation does do is respond to change. Most of the neurons in the core of the hindbrain and the midbrain are of this curious non-specific nature. They sit with their dendrites --their cellular hands--spread across several millimeters, hoping to catch any kind of message (ref 5).

This differs from the rest of the brain where neighborhood is so rigorously maintained. Two sensory neurons that are neighbors on the skin will end (after passing through several synapses) as neighbors in the cortex. Each of the senses has its own landing area; they do not mix until they filter through the koniocortex. The reticular formation is different; it accepts signal energy from any sensory modality. Looking at the arrangement, we see no hope of anything but noise. "The situation nonetheless prevails in the brain of all vertebrates. One must therefore suspect that its existence corresponds to a particular need." (ref 5) That is exactly what does happen; the input of the reticular formation is noise. But it is noise with a level, and the

level is the message. We awake to a touch and being awake, recognize it as a touch. We say the touch woke us. Not so. The "noise" woke us, and then we recognized the touch. "Electrical stimulation of the brain stem reticular formation or natural stimulation of spinal or cranial sensory nerves produces widespread cortical activation or desynchronization, i.e., the high voltage-slow wave electroencephalogram (EEG) of quiet relaxation is replaced by the low voltage-high frequency EEG of intense wakefulness." (ref 1)

The world of living things is a world of survivors. To be a survivor we must reproduce, and we must eat and evade the predator until we can. A bottom filter feeder can eat and mate by following his nose. Hardwiring that causes the head to turn up gradient on sensing an odor (genetically rated good) coupled with a forward motion will do the job. Evading the predator requires a brain; we must monitor the environment and produce an evasive action as required.

ANATOMY

We use the anatomical description of the brain; there are no common names. The brain is a collection of independent neurons. The neuron is a specialized cell--specialized to send and receive electrical potentials. It usually passes a potential by releasing atoms but may pass them by direct ionic current.

The neuron exists as a collection of molecules. All its actions are molecular. The ions that enter at the synapses originate from a strictly numbered set of neurons from as few as two or three (in the lateral geniculate) to as many as 20,000 (a Purkinje cell in cerebellum). The neuron knows nothing beyond the momentary *condition of the neurons afferent* on it and those to which it is efferent. Molecular activity is enough to explain its actions.

Figure 3 is a generalized neuron with dendrites and an axon. It stands for the myriad of forms that the neuron takes. There are also neurons without axons and neurons without dendrites. Neurons use at least three methods to talk to each other: gap junctions, ephaptic interactions, and the release of neurotransmitters. Gap junctions bring channels in the membranes of two neurons into alignment so that ions can flow directly from one cell to the other. Ephaptic interactions occur when the processes of two neurons parallel each other so that an electric current in one neuron causes an electric current to flow in the other. The release of neurotransmitters is the favorite mode. Synapses cover the dendrites, the soma, and the initial portion of the axons; we show only one. When a depolarizing potential arrives at a pre-synaptic site, it releases molecules of a neurotransmitter into the synaptic cleft. The molecules cause an ionic flow, either in or out or both, in the post-synaptic cell by opening gates in the cell membrane. These ionic flows alter the behavior of the neuron. There are many neurotransmitters and many configurations of synapses and the details are fascinating, but for our purposes we simply say that it is at the synapse that one neuron affects another. It is not proper (though we do it) to speak of a neuron as "active" or "turned on." We may say of some neurons that over a given period they produced more axonal pulses than they did over another period. It might be better to say that a neuron is turned up or turned down. Some neurons, of course, have no axons. One thing is certain, we cannot represent a neuron by a term in a logical equation that has the quality of "on" or "off." We cannot say that the brain has states and proceeds from one to another. Symbolic logic is wholly inadequate to describe the brain. A

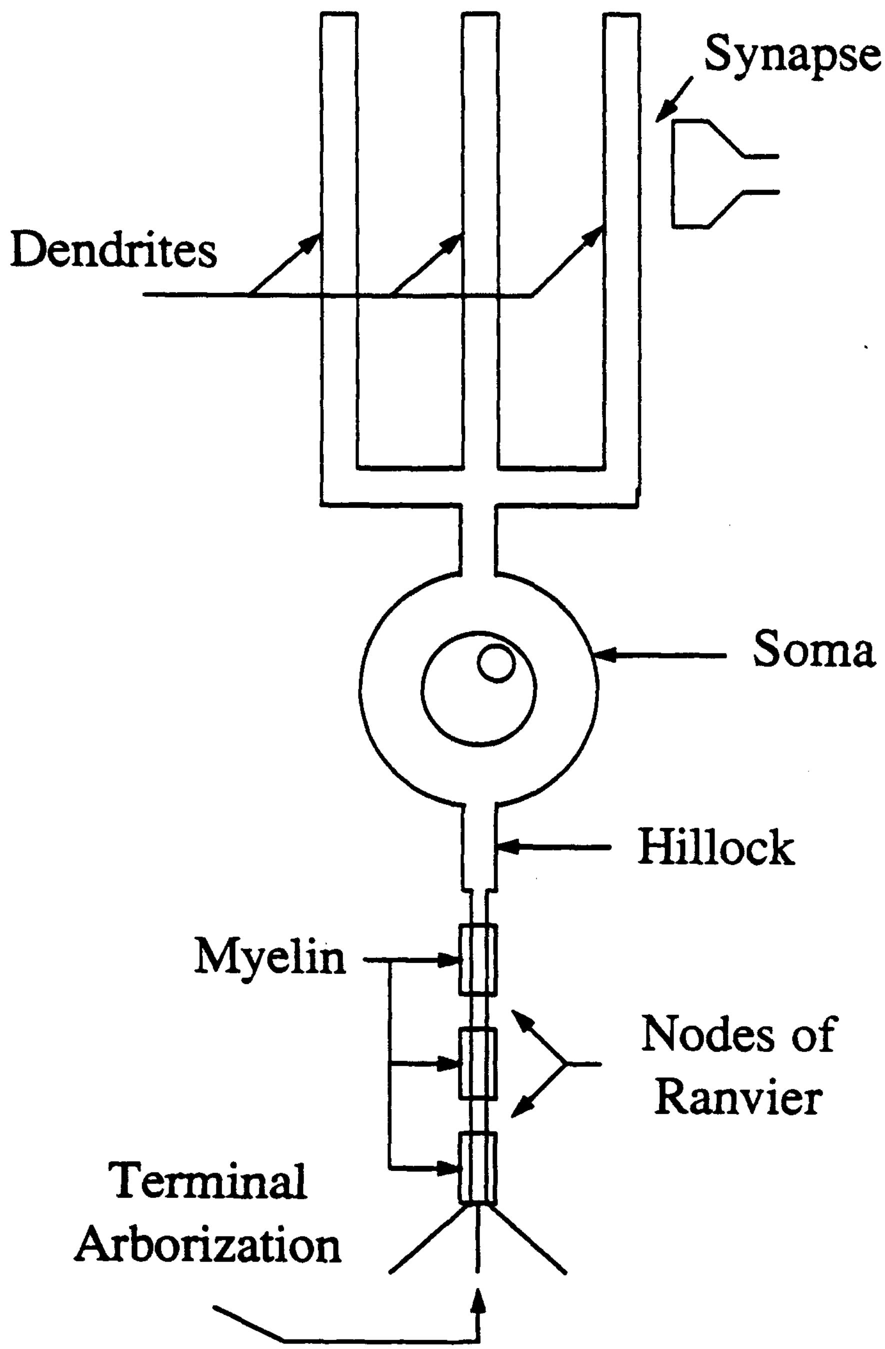

Figure 3. A generalized neuron.

neuron does not pass information; it does not encode information; it does not extract features. It is only more or less active.

If the ionic flows in a neuron are such that a depolarizing potential comes to exist at the axon hillock, this depolarization moves down the axon as an axonal pulse. Oligodendroglial cells (Schwann cells in peripheral nervous system (PNS)) encircle the axon, forming an insulating sheath called myelin. The nodes of Ranvier break the insulation at intervals. Between nodes the pulse travels as an electrical current. At the nodes the ionic mechanism that created the pulse at the hillock again comes into play. Thus the pulse can move at high speed while retaining its amplitude. When it arrives at a pre-synaptic site, it will cause the release of a neurotransmitter.

The axons grow to make connections, but the genome provides the rules for the growth. The axon of an exercised neuron grows and establishes synapses; an inactive neuron attracts synapses or it dies. Signal energy flowing through the brain results in the organism springing into action, or sleeping, or observing quietly.

The Brain

The traditional illustration of the brain shows the cerebral hemispheres as if they were the whole; Figure 4 is an alternative. The neocortex has shrunk to a small box while we give more space to other parts of the brain in keeping with their importance. Although man is a microsmatic animal, his nose is still of importance to him. We show the olfactory system large to reflect this. Also we show it large because of its importance in the evolutionary history of the brain.

The brains of vertebrates share a common structure: a spinal cord surmounted by a rhombencephalon, a mesencephalon, and a prosencephalon. We speak of man's brain, but our knowledge is mostly of the brains of rats, cats, and monkeys. The rat's brain has everything that a man's brain has, only the parts are smaller. It is no small feat to distinguish between a section of a rat's cortex and that of a human. Current techniques of tract tracing are invasive and can't be used on humans. Human brains are usually not even available after death until a decent interval has passed--an interval that is long enough for the brain to start to digest itself.
The brain is really two brains. There are two of almost everything, but (barring people who have had their brain surgically split to treat epilepsy) the two brains function as one. This doubled nervous system is responsible for our perception of a three-dimensional world; with more systems we should see more dimensions.

The central nervous system (CNS) is a sensory system with information flowing up and fanning-out, and a motor system with information fanning-in and flowing down to the muscles. We divide the CNS into brain stem, cerebellum, diencephalon, basal ganglia, and cortex. This division is as good as any other.

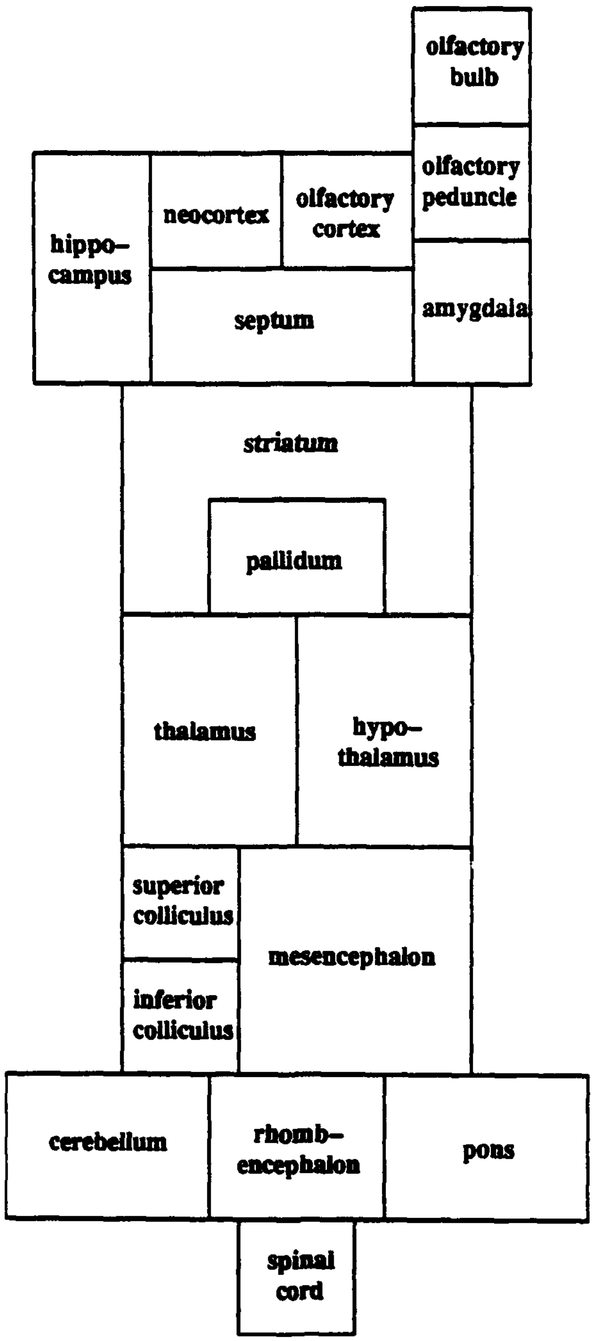

Figure 4. The mammalian brain.

The Brain Stem

The brain stem is very old, very conservative, and contains the control centers for important biological functions. The lower part of the brain stem divides into the medulla (a continuation of the spinal cord) and the pons. The medulla controls breathing and the circulation. The pons contains the sleep-wake and alerting mechanisms.

The upper part of the brain stem, the mesencephalon or midbrain, contains the superior and inferior colliculi. Originally, as the optic tectum, the superior colliculus was a terminus, but now most visual signal energy flows through the lateral geniculate body. Similarly the inferior colliculus is now a way station for somatic (body) stimuli and for auditory signals on their way to the medial geniculate body.

Buried in the brain stem are three structures that run its length: the reticular formation, the median forebrain bundle, and the periaqueductal gray. These are the alerting, the pleasure, and the pain systems, respectively.

The Locus Coeruleus

There is a sleep center in the locus coeruleus that shuts down the organism by turning on the reticular nucleus of the thalamus. The inhibition is complete. The reticular nucleus inhibits the ventral anterior-ventral lateral complex, the geniculate bodies, and the ventral medial lateral nucleus. Sleep is not merely a passive process of reduced activity in the reticular formation. It is an active process of neuronal activity in the locus coeruleus. A turn of the sleep-wake cycle activates the reticular formation. When it is active, part of the signal energy flows through to lower the threshold of the brain and to inhibit the reticular nucleus of the thalamus. This turns on or prepares the brain for incoming signal energy. A diurnal clock toggles the sleep-wake cycle. It keeps in phase with the day-night cycle by monitoring the visual input (ref 1).

The sleep mutation survived when the day (or year) contained a period in which there was more chance of being eaten than of eating. The energy expended in acquiring food must be less than, or equal to, the energy gained in eating it. The relentless balancing of the energy equation explains the retreat into the burrow. The burrow gives some protection from the predator; sleep reduces energy expenditure through the negative period. That is all there is to sleep.

The Cerebellum

Skilled behavior is a weighted average of past experience. The synapses on the Purkinje cells in the cerebellum keep this running average of experience. The upward output of the cerebellum, the superior cerebellar peduncle or brachium conjunctivum, enters the ventral lateral posterior nucleus of the thalamus. The thalamus relays the motor program to the motor cortex where another motor program joins it. This second program came from the globus pallidus interior via the ventral lateral anterior nucleus and the pre-motor cortex. The globus pallidus supplies the gross structure of a movement; the cerebellum provides the refinements. The globus pallidus can hit the piano keyboard with paw-like movements; the cerebellum sequences the fingers as they strike the keys. The programs in the globus pallidus are hardwired by the genes,

but those in the cerebellum come from experience.

The Diencephalon

Between the mesencephalon or midbrain and the cerebral hemispheres lies the diencephalon--the center of consciousness. It is here that we really live; it is here that we are aware of the brain thinking (ref 6). The dorsal two-thirds of the diencephalon is the thalamus and the ventral part is the hypothalamus. The hypothalamus extends rostrally as the septum and ventrally as the pituitary complex. The septum is the pleasure center; whatever excites the septum is good. The original motor programs of going forward toward "good" and turning away from "bad" have evolved into all those things we think of as human responses to the world. The hypothalamus is the seat of the basic responses of the body. While the amygdala contains the wiring that detects the threat, the hypothalamus starts the reaction; it is the center of rage and of cold attack. The thalamus is the center of hesitation. It is the thalamus that delays response that causes the organism to "think before jumping."

The thalamus is a group of some sixty seemingly unrelated nuclei sitting in the center of the brain. Diligent investigation has sorted these nuclei into at least five classes arranged by function:

1. The lateral and medial geniculate bodies and the ventrobasal nucleus that relay signal energy on its way in.

2. The ventral anterior and the ventral lateral nuclei that relay motor programs on their way out.

3. The "association" nuclei, the mediodorsal and the lateral nuclei that exchange axons with frontal association cortex and the association field that lies between the seeing, hearing, and somatic areas of cortex.

4. The emotional nucleus, the anterior nucleus that interacts with the limbic system.

5. The nonspecific nuclei that seem to get input from just about anywhere and relay it most anywhere except the sensory fields.

Only one thing is certain; with the exception of the reticular nucleus of the thalamus, none of these cell groups communicate directly with one another (ref 5).

What then can the thalamus do? It can relay signal energy and it can NOT relay it. It can be: (1) completely open, allowing all information to pass to the cortex; (2) completely closed, cutting off the cortex from the outside world; and (3) partially open, allowing selected signal energy to pass (ref 7). This interference with the passage of signal energy is the higher function of the brain.

The Reticular Nucleus of the Thalamus

Figure 5 is an abstraction of the mammalian brain. The fan-out and the fan-in occurs in the neocortex and the basal ganglia. Signal energy flows in and motor programs flow out through the thalamus. In position to halt this flow is the reticular nucleus of the thalamus. The reticular nucleus is a thin sheet that covers most of the anterior, lateral, and ventral surfaces of the dorsal thalamus. The axons of the thalamic radiation pierce it. The nucleus includes overlapping sectors, each of which associates with a particular dorsal thalamic nucleus. The thalamocortical and corticothalamic fibers that give off collaterals as they pass through embody this relationship. The principal neurons of the reticular nucleus project to the nucleus of the dorsal thalamus that is the origin (or destination) of these fibers and the axons ramify wide There are no interneurons (ref 8).

We must not confuse the reticular formation and the reticular nucleus of the thalamus. They are wholly separate, distinct parts of the brain; "reticular" refers only to their physical appearance.

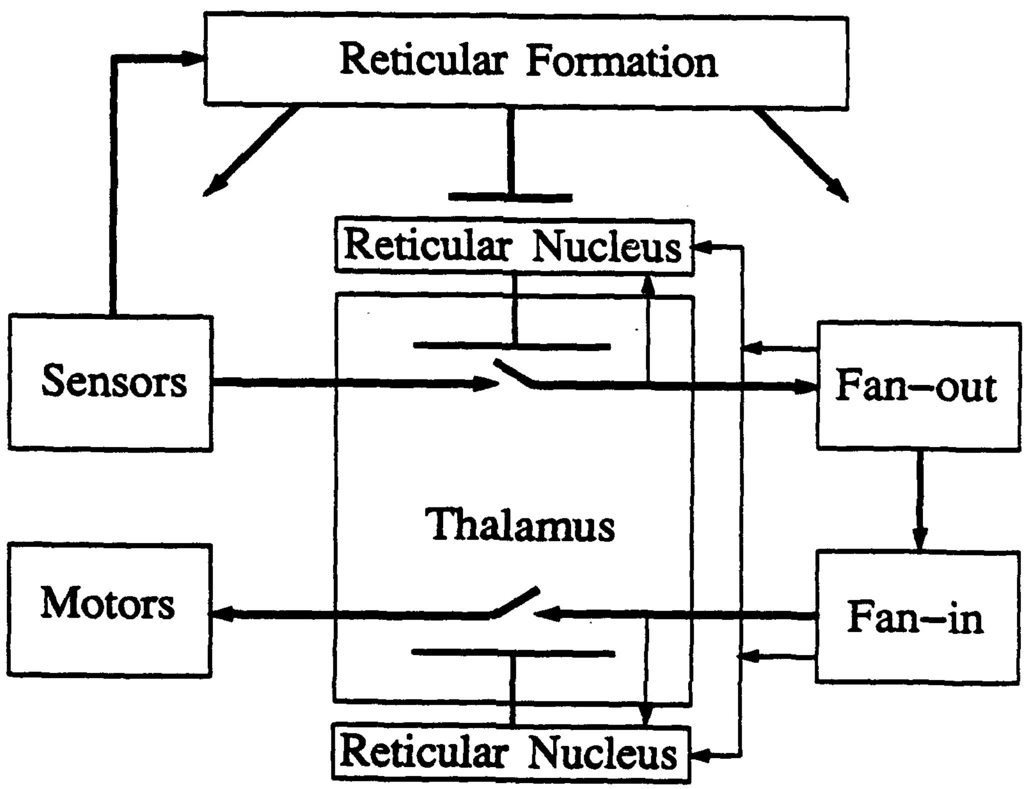

Figure 5. The essential structure of the working mammalian brain.

The reticular nucleus of the thalamus operates by simple consensus. If there is enough excitatory energy flowing into it, it will inhibit the thalamus; if there isn't, it won't. The reticular nucleus receives energy from all the axons that traverse it from the thalamus and from the cortex, but the input that interests us the most comes from the prefrontal area of the cortex. It is here that we learn right from wrong--what leads to good and what leads to bad.

The signal energy uses the reticular nucleus of the thalamus to turn off the relays. This need not happen, of course; the relays could remain on indefinitely. This would parallel the action in simpler brains. The mammal would be like a reptile; presented with food, it would eat. But this is not the case. Periodically, eight to ten times a second, the reticular nucleus interrupts the flow of signal energy. This delay gives the signal energy a chance to propagate for a fraction of a second, free from being overridden by new input (ref 9).

If the present milieu and the suggested action have lead to trouble in the past, this trouble potentiated the excited synapses in the thalamic reticular nucleus. Now the reticular nucleus is active; it inhibits the relay of the motor program from the basal ganglia to the pre-motor area of the cortex. The motor action does not occur. The reticular nucleus inhibits sensory input and prior signal energy moves around in the cortex and the basal ganglia until a motor program turns on that does not have a bad history. The activation of the reticular nucleus ceases, and the motor program flows through to the pyramidal tract.

This action does not take place in a vacuum. The signal energy that activates the reticular nucleus opposes the energy from the reticular formation that is inhibiting the reticular nucleus and can be said to be "demanding action." It is the summation of these competing energies that determines the event.

Hesitation

The nominated motor program and the present signal energy may (depending on past events) activate the reticular nucleus of the thalamus. This inhibits the ventral lateral anterior nucleus of the thalamus and stops the motor program on its way from the globus pallidus interior to the pre-motor cortex (area 6). From the pre-motor cortex the motor program would have continued to the motor cortex where it would have joined the final adjustments coming from the deep cerebellar nuclei via the ventral lateral posterior nucleus. The reticular nucleus also inhibits this cerebellar output. We must say again that a motor program is not a computer program--it is just our name for the impulses that flow from a group or constellation of activated neurons. Signal energy flows in from the senses and at some point we start calling it a motor program.

Decision

During hesitation the signal energy oscillates between the cortex and the basal ganglia, turning into one motor program after another. It does not dissipate; the brain delicately adjusts itself so that the signal energy neither dies out nor explodes into epilepsy. When one with less "trouble" connotations emerges, energy no longer flows through to keep the reticular nucleus activated. The energy from the reticular formation becomes dominant and inhibits the reticular nucleus. The motor program flows through the ventral lateral anterior and ventral lateral

posterior nuclei of the thalamus and on to the pre-motor and motor cortex. This is not the search strategy that is popular with theorists. Only a closely allied group of motor response neurons will be nominated repeatedly with slight variations. If none is acceptable, either the demand for action will override the barrier or the neurons will be exhausted and allow a new objective to come into view.

Action Under Pressure

Signal energy from the reticular formation overrides the "trouble" energy; it inhibits the reticular nucleus of the thalamus and action follows. It may lead to trouble, but there is action.

Delayed Decision

Absent pressure from the reticular formation, the reticular nucleus continues its inhibiting activity, and the signal energy oscillates between the cortex and the basal ganglia. The ventral lateral nuclei do not relay the motor programs to the pre-motor cortex. This continues indefinitely; we call it "thinking"; it is what mathematicians, physicists, and chess players do.

The Basal Ganglia

The paleocortex (old bark) came from the olfactory lobe in amphibia and fits like a cap over the thalamus. The inner part, the basal ganglia (caudate nucleus, putamen, globus pallidus, and some smaller nuclei), contains the motor programs that make up behavior. The activity of the outer part (hippocampus, septal area, amygdala, and the cingulate gyrus) involves memory and emotion. Memory is the excitation of a subset of the neurons that the original experience excited. The connection is through the hippocampus. Emotion is the excitation of parts of the other nuclei.

The striatum (caudate nucleus and putamen), the globus pallidus, substantia innominata, ventral pallidum, the basal nucleus of Meynert, substantia nigra, the ventral tegmental area, and the subthalamic nucleus are the basal ganglia. This is the region where signal energy transforms itself into motor programs. It is still signal, but it is time to look ahead to its return to the exterior world through the muscles. A motor program is a set of neurons that can produce impulses properly sequenced so that when they arrive at motor neurons, a fluid movement of the animal follows. The program is only a rough template; it must be adjusted by the Purkinje neurons in the cerebellum for smoothness and elegance.

The projection of the neocortex on the striatum is the interface between fan-out and fan-in. All parts of the cortex project to the striatum and here signal energy stops its spreading out and starts to come together on its way to the muscles. The striatum projects to the globus pallidus. The signal energy activates neurons that produce a pattern to move toward or away. The signal energy continues down the ansa lenticularis and the larger portion enters the rostral part of the ventral nucleus of the thalamus. This rostral part is the ventral anterior nucleus and the ventral lateral nucleus. The ventral lateral anterior nucleus relays the signal energy to the pre-motor cortex; from the pre-motor cortex it flows to the motor cortex. The ventral lateral posterior nucleus relays the portion of the signal energy that passed through the cerebellum direct to the motor cortex. From the motor cortex, the combined energy flows to the muscles.

The olfactory sense produced the forebrain. It is no longer stylish to refer to it as the rhinencephalon, the nose-brain. The olfactory bulb is important to the primitive vertebrate; vision alerts it to the predator, but olfaction leads it to food and a mate. All it needs are neurons that respond to "good" smells and produce a motor response in the direction of the nostril with the stronger response. The brain evolved as a series of refinements to this basic action.

The Neocortex

The neocortex (new bark) forms the great mass of the cerebral hemispheres that hides the remainder of the brain and is the part that illustrators usually show. Frontal, temporal, parietal, and occipital lobes are the usual place names. Since few animals have a larger cerebrum than man, the neocortex has always fascinated writers as the thing that differentiates man from other animals. We prefer to see the neocortex as merely the backplane that the nuclei of the thalamus and the basal ganglia use to talk to one another.

The periphery of the nervous system contains a variety of transducers that transform physical and radiant energy into the electrochemical energy of the brain. These transducers monitor both the exterior universe and the interior world of the body. All this incoming energy, irrespective of source, we label signal energy. This signal energy is the sole input to the brain. Since a neuron has absolutely no way of determining the source of neurotransmitters impinging on its synapses, we will consciously refuse to divide signal energy by its origin; visual, auditory, somatic--it is all one.

After landing in the koniocortex, the signal energy fans-out through the association cortex. These neurons stand ready to be excited by patterns and combinations of patterns. Nothing else happens during the fan-out. As an example of this filtering, oriented line segments excite certain cells in the visual cortex, and line segments undergoing orthogonal displacement excite others. Combinations of these cells excite still others. Usually the excited neurons feed back part of the energy to the cells that excited them.

The genome establishes these patterns and they are completely arbitrary except that they survived. They control our understanding of the universe of experience, but not the experience itself. We experience the visual scene (as we do any other sense) as a whole. We perceive the components through the pattern activity. We see a dog... a cascade of pattern filtration in the neocortex turns up all the neurons that animals, dogs, and this particular dog have turned up previously. We can now say it is a dog, give its name, respond properly in a human fashion to the presence of a dog. Cortical damage can remove these extras, but we will still see a dog; we will see a dog, but we will not respond to it.

The existence of the cells in the fan-out (the association cortex) defines the possibilities of the differentiation by the brain. The kitten, exposed only to horizontal lines during a crucial period, can never see vertical lines. For the kitten, the vertical lines do not exist. It cannot see them...not now...not ever. The needed cells that the genome furnished for vertical lines are dead or used for other purposes. We cannot emphasize too strongly that it is we, the observers, that speak of oriented line segments. The neuron in the kitten's brain only knows the neurons that are afferent on it.

The number of neurons available limit the number of patterns possible. The genome determines the kinds of combinations. There is plasticity and this plasticity is the basis of education, but if the genome does not provide the pattern, we cannot experience it. We cannot imagine combinations we do not have. What notion can the colorblind have of color? What notion can the blind have of sight?

Fan-in follows fan-out; the signal energy has spread out through the cerebrum, now it funnels into the striatum. It turns up fewer and fewer neurons until it reaches the final pattern that determines the motor response. The march of the signal energy is not simple, there is almost endless feedback. The motor output leads to results that are good, bad, or indifferent. If the result is bad, it activates the posterolateral and intralaminar nuclei of the thalamus. They originate pulses that arrive at, among others, the prefrontal area. The genome wired these axons to cause potentiation of recently fired synapses. If the same (or nearly the same) signal energy flows in again, it will activate the same motor program and flow through the potentiated synapses to activate the reticular nucleus of the thalamus. The motor program will not flow through the ventral anterior-ventral lateral nuclei of the thalamus and will not reach the motor area of the neocortex. Not only will the reticular nucleus stop the motor program, but their refractory period will temporarily remove the program neurons from the action. This allows the signal energy to take a path through an alternate motor program that may not have the same "trouble" record. If so, the reticular nucleus will not continue to be activated, and the motor program will flow through to the motor section. This is all there is to thinking.

The Hippocampus

Memory is the effect that prior signal energy has on a later flow. We can distinguish short, medium, and long-term memory. The hypopolarization that follows the immediate hyperpolarization after a neuron fires provides the short term effect. This hypopolarization makes the neuron easier to fire for a short period. This is the physical basis of our ability to look up a telephone number and hold it "in our head" until we dial it. Pain, pleasure, or novelty potentiate synapses in the hippocampus. The neurons involved have widespread reciprocal connections to the rest of the brain and with each other. If signal energy turns up a neuron in the hippocampus, it will turn up others that participated in this potentiation. This effect is much longer lasting. We experience this subjectively as a train of thought. We say that A reminds us of B.

Truly long-term memory, which survives the surgical excision of the hippocampi, depends on the repeated activation of a neural constellation through the hippocampus. This repeated firing, over a period of years, slowly potentiates reciprocal synapses between the neurons involved until the constellation can be activated without the presence of the key neurons in the hippocampus.

The Amygdala

The amygdala responds to danger; it reacts to a friend or to the enemy. The genes hardwire it to respond to combinations of signal energy that have proved either supportive or threatening in the species history. The experience of "things moving toward" is most important. An individual moving directly toward with his eyes fixed on us is the worst sort of threat.

The male stickleback sees anything with a red underside as a rival and attacks it viciously. A piece of wood, looking nothing like a fish which we have painted red on the bottom, is assaulted. If we reverse the block so the red is on top, the stickleback ignores it. For the female, the reverse is true. Red belly is attractive (ref 10). If we rotate the block slightly so that the red part is still below but the top surface partly presents itself, this little block of wood enrages the male stickleback. He perceives the head down threat position of another male.

All this is only the result of a simple homeostat. A little introspection finds it in our own approach to the world.

RECAPITULATION

Thought is a movement that is not connected to a motor neuron. The disconnection is effected by the reticular nucleus of the thalamus. It inhibits the ventral lateral anterior nucleus and stops the relay of the motor program from the globus pallidus interior to the pre-motor cortex. At the same time it inhibits the ventral lateral posterior nucleus and stops the relay of motor refinements from the cerebellum to the motor cortex. The reticular nucleus is activated by the trouble history of the movement, especially as recorded in the pre-frontal cortex. Thinking also depends on the reticular nucleus inhibiting the relay of signal energy to the neocortex so that new signal energy will not upset the reverberation of the old.

EPILOGUE

That is all there is to the story of the brain: a homeostat that the genes wired for survival. In man, hesitation and deliberation can become dysfunctional leading to philosophy and mathematics.

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GLOSSARY

afferent To the receiving neuron, the synapse is afferent.
amphibia A class of vertebrates, intermediate between fishes and reptiles.
amygdala Nucleus of the limbic system in the base of the temporal lobe.
ansa lenticularis Output tract of the globus pallidus interior, the greater part of which curves back and enters the ventral lateral anterior nucleus of the thalamus.
anterior Toward the front.
association cortex Cortex that is not the target of sensory information.
axon Part of a neuron that transmits impulses to other neurons or effectors.
axon hillock The initial segment of the axon adjoining the soma.
backplane The back wiring of a computer, now replaced by motherboard.
basal ganglia A group of large nuclei in the forebrain with important functions in regulating body movements.
basal nucleus of Meynert One of the basal ganglia.
brachium conjunctivum The superior cerebellar peduncle.
brain stem Mesencephalon, pons, and medulla oblongata.
caudal Toward the tail.
caudate nucleus The tailward part of the striatum.
cerebellar peduncle Attaches cerebellum to brain stem.
cerebellum Specialized part of hindbrain; stores learned refinements to motor programs.
cerebral hemispheres Two major parts of the forebrain in mammals; functions as a backplane.
cingulate gyrus Strip of limbic cortex just above the corpus callosum along the medial walls of the cerebral hemispheres.
CNS Central nervous system; the brain and spinal cord.
consensus The response of a neuron to the majority of a large number of neurons.
constellation The neurons that make up a percept, a concept, the response to the concept, or all three.
cortex Bark or outer layer of an organ such as the cerebrum, cerebellum, or adrenal gland.
corticothalamic Proceeding from the cortex to the thalamus.
cranial Of the skull.
dendrite Tree-like branches of a neuron that receive impulses and graded potentials.
depolarize To move the membrane potential toward zero.
desynchronization No longer made to fire together.
diencephalon A region of the brain that includes the hypothalamus, thalamus, and epithalamus.
dorsal Toward, or on, the back.
efferent To a transmitting neuron, the synapse is efferent.
electrochemical Marked by electric currents made up of charged atoms.
electroencephalogram (EEG) A record of electrical potentials from the surface of the scalp that measure brain wave activity.
endocrine System of ductless glands that secret directly into the blood stream.
ephaptic interaction One neuron passing a potential to another through proximity alone.
fan-in The concentration of signal energy from cortex into the basal ganglia.
fan-out The spreading out of signal energy from the koniocortex into the association cortex.
feedback Originally the return of energy from the output of an oscillator to its input; now the return of signal energy in general.
fiber An axon.

fine-tune To use an auxiliary capacitor to adjust the frequency of a tuned circuit.
forebrain In mammals the cerebral hemispheres, thalamus, and hypothalamus.
frontal Of the forehead.
frontal association cortex Cortex beneath the forehead without direct sensory input.
gap junction Aligned channels in two neurons allowing direct interchange of ions.
gene Functional unit of the chromosome that directs protein synthesis.
genome One haploid set of chromosomes.
globus pallidus The inner zone of the corpus striatum.
graded potential A potential field that varies in time but not so abruptly as a pulse.
habituation Gradual decrease of response to a maintained or repeated stimulus.
hindbrain Primitive parts of the mammalian brain that include the cerebellum and the medulla.
hippocampus A forebrain structure of the temporal lobe that is crucial in learning.
homeostasis A relatively stable state of equilibrium.
homeostat A mechanism that effects homeostasis.
homunculus A fully formed miniature human body believed, according to some medical theories of the 16^{th} and 17^{th} centuries, to be contained in the spermatozoon.
hyperpolarize Move the membrane potential away from its resting value and away from zero.
hypopolarize Move the membrane potential away from its resting value and toward zero.
hypothalamus Part of diencephalon beneath the thalamus.
inferior colliculus Protrusion of the midbrain that relays auditory information.
interface A surface that separates the nervous system from the remainder of the universe.
internet All the neurons between the sensory and motor neurons.
interneuron A neuron in the internet; sometimes restricted to those in direct contact with sensory neurons.
intralaminar nuclei Thalamic nuclei of obscure function.
invasive A procedure that destroys the integrity of the body.
ion An electrically charged atom.
koniocortex The primary sensory fields of the neocortex.
lateral Of the side.
lateral geniculate body A group of cell bodies within the thalamus that receive impulses from the retina and relay them to the primary visual area of the cortex.
limbic system A group of subcortical structures including the anterior thalamus, amygdala, hippocampus, and parts of the hypothalamus that mediate drive-related behavior.
locus coeruleus The sleep center in the midbrain.
logical equation An equation with terms having truth value.
materialism The doctrine that matter and its motions constitute the universe; presently fashionable amongst Anglo-Saxon philosophers.
medial geniculate body A thalamic nucleus that relays auditory signal energy.
median forebrain bundle A complex tract running from the hindbrain and the midbrain and innervating essentially everything in the forebrain; associated with pleasure.
medulla oblongata Nervous tissue at the base of the brain that controls respiration, circulation, and other vital functions.
membrane The outer skin of a cell.
mental component The subjective part of a mind-brain action.
mesencephalon The midbrain.
metabolism The processes of building up and tearing down of protoplasm, incidental to life.
microsmatic Placing relatively lesser importance on the sense of smell.

midbrain Part of the brain that includes centers for sensation, movement, and arousal.
milieu The environment.
motor A muscle, an effector.
motor area Area 4 of Brodmann; the origin of the pyramidal tract; important in movement.
motor program A constellation of neurons that will sequence muscles to perform a maneuver.
myelin An insulating covering of the axon.
neocortex Newest part of the cerebral cortex.
neural tube A neural plate appears on the surface of the embryo; it buckles inward and forms the neural tube; this becomes the brain and spinal column and leads to all the wonders of intelligence.
neuron A nerve cell with its processes; the basic functional unit of the central nervous system.
neurotransmitter Chemical substance released at the terminal of an axon that travels across the synaptic cleft and may excite or inhibit the target neuron.
node of Ranvier A periodic interruption of the myelin.
nucleus accumbens septi A rostral extension of the hypothalamus; the seat of pleasure.
occipital Posterior lobe of cerebral hemisphere.
olfaction Sense of smell.
olfactory lobe The internet for smell in amphibia; becomes the olfactory bulb and the olfactory cortex in mammals.
oligodendroglial The myelin-forming cells in the central nervous system.
optic tectum The equivalent of the superior colliculus in animals more primitive than mammals.
organism A living system with the capacity to respond to external stimuli, metabolize, grow, learn, and respond (depending on feedback) to the environment.
osmoreceptor Senses osmotic pressure.
parietal The lobe of the cortex between the frontal and the occipital.
periaqueductal gray A hindbrain and midbrain tract terminating in the thalamic posterolateral nucleus; central to pain.
peripheral External; away from the central nervous system.
peripheral circulatory system The blood system that supplies the outer part of the body.
piloerection Erection of body hairs.
pituitary complex The hypophysis; the posterior lobe, the neurohypophysis, is a true part of the brain; the anterior lobe, the adenohypophysis, is not part of the brain.
placode Local thickening of the epithelial layer in the embryo.
plastic Capable of building or shaping tissue and altering synaptic transmissibility.
PNS Peripheral nervous system.
pons Part of the metencephalon.
post-synaptic Target neuron that receives neurotransmitter from a pre-synaptic neuron.
posterolateral nucleus Thalamic nucleus that is at the heart of subjective pain.
potential The degree of electrification between two points.
potentiate To increase the efficacy of a synapse.
predator One that lives by eating other animals.
prefrontal Cortex in front of the motor area.
pre-motor area An area of the neocortex adjoining the motor area; areas 6 and 8 of Brodmann.
preopticanterior A hypothalamic region.
pre-synaptic site The efferent side of a synapse.
principal neuron A neuron with a long axon that carries a signal to some other area.
process An extension of a cell.

projection The general course of axons leaving a brain region.
prosencephalon The forebrain.
putamen The rostral part of the striatum.
radiant energy Energy transmitted in wave motion.
receptor A sensory cell that transduces physical stimuli into graded potentials that alter the rate of firing of interneurons.
reciprocal connections The mutual interchange of axons between two regions of the brain.
relay nucleus A thalamic nucleus that relays signal energy to the neocortex.
reticular formation A large network of neural tissue located in central regions of the brainstem, from the medulla to the diencephalon.
retina Photoreceptive inner surface of the posterior portion of the eye.
rhinencephalon The nose-brain.
rhombencephalon The hindbrain.
rostral Toward the beak (mouth).
Schwann cell A cell that makes up the myelin in the peripheral nervous system.
sensor A transducer; converts one form of energy to another.
septal area See nucleus accumbens septi.
septum See nucleus accumbens septi.
signal energy The totality of energy crossing the interface and entering the central nervous system.
soma Body.
state The notion that the universe, or any part of it, can be described by a vector of elements having truth value or that are numbers; a conceit of the logicians.
striatum The outer zone of the corpus striatum.
subjective Pertaining to the awareness of a mind.
substantia innominata One of the basal ganglia.
substantia nigra One of the basal ganglia.
subthalamic nucleus One of the basal ganglia.
superior colliculus Protrusion on top of the midbrain serving to provide spatial information.
symbolic logic Mathematical logic; a formal system using symbols and a manipulative algebra to describe thought.
synaptic cleft A 200 nanometer space between the pre-synaptic and the post-synaptic sites.
synapse Gap or junction between neurons across which signals that modify behavior are transmitted.
temporal Behind the temple.
term Element in an equation.
terminal arborization The branching out of an axon at its end that may be so profuse as to resemble a bush or tree.
thalamic radiation The great net of axons from the thalmus that sweep out to the cortex.
thalamic reticular nucleus A thalamic nucleus in the form of a thin sheet that envelops the dorsal thalamus.
thalamic ventral posterolateral See ventral lateral posterior nucleus.
thalamocortical Proceeding from the thalamus to the cortex.
thalamus A large ovoid mass of gray matter in the diencephalon that some see as the center of awareness.
threshold A critical potential at the hillock, depolarizing below which lea. to the generation of a pulse.

toggle To flip a two-position switch.
topology A branch of mathematical geometry that describes the invariant features of an object or pattern despite transformations of size.
transduce Convert from one form of energy to another.
vasoconstriction Constriction of the smaller blood vessels.
vasodilation Dilation of the smaller blood vessels.
ventral Of or toward the belly.
ventral anterior-ventral lateral complex The general area of the thalamus that relays motor programs.
ventral lateral posterior nucleus The thalamic nucleus that relays cerebellar motor programs.
ventral lateral anterior nucleus The thalamic nucleus that relays motor programs from the globus pallidus interior.
ventral pallidum Ventral part of globus pallidus.
ventral tegmental area One of the basal ganglia.
ventrobasal nucleus Thalamic relay nucleus for somatic signal energy.
vertebrate Having a backbone.

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